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Hydrology and Earth System Sciences Discussions

Hydrology and Water Resources Management in Ancient India

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Abstract. Hydrologic knowledge in India has a historical footprint extending over several millenniums through the Harappan Civilisation (~ 3000 BC – 1500 BC) and the Vedic period (~1500-500 BC). As in other ancient civilisations across the world, the need to manage water propelled the growth of hydrologic science in ancient India also. Most of the ancient hydrologic knowledge, however, has remained hidden and unexplored to the world at large till the recent times. In this paper, we provide some fascinating glimpses into the hydrological, hydraulic and related engineering knowledge that existed in ancient India, as discussed in contemporary literature and in the recent explorations and findings. The Vedas, particularly, the *Rigveda*, *Yajurveda* and *Atharvaveda* have many references to water cycle and associated processes, including water quality, hydraulic machines and other structures and nature-based solutions (NBS) for water management. The Harappan Civilization epitomizes the level of development of water sciences in ancient India that includes construction of sophisticated hydraulic structures, wastewater disposal systems based on centralized and decentralized concepts as well as methods for wastewater treatments. The Mauryan empire (~ 322 BC – 185 BC) is credited as the first "hydraulic civilization" characterised by construction of dams with spillways, reservoirs, channels equipped with spillways, pynes and *Ahars*, understanding of water balance, development of water pricing systems, measurement of rainfall and knowledge of the various hydrological processes. As we investigate deeper into hydrologic references in ancient literature, including the Indian mythology, many fascinating dimensions of the early scientific endeavours of Indians emerge.

1 Introduction

Water is intimately linked to human existence and is the source of societal and cultural development, traditions, rituals and religious beliefs. The humans created permanent settlements about 10,000 years ago when they adopted an agrarian way of life and started developing different socio-cultural societies and settlements, largely dependent on water in one way or other (Vuorinen et al., 2007). These developments established a unique relationship between humans and water. Most of the ancient civilizations, e.g., the Indus Valley, Egyptian, Mesopotamian, and Chinese civilizations were developed at places where water required for agricultural and human needs was readily available, i.e., in the vicinity of springs, lakes, rivers and low sea levels (Yannopoulos et al., 2015). As water was the prime mover of the ancient civilizations, a clear understanding of the hydrologic cycle, nature and pattern of its various components along with water uses for different purposes led these civilizations to flourish for thousands of years.

The Harappan (or Indus Valley) civilization (3000 BC – 1500 BC), one of the earliest and most advanced civilizations, was also the world's largest in spatial extent and epitomises the level of development of science and society in proto-historic Indian sub-continent. Jansen (1989) states that the citizens of Harappan civilization were known for their obsession with water; they prayed to the rivers every day and accorded the rivers a divine status. The urban centres were developed with state-of-the art civil and architectural designs with provisions of sophisticated drainage and waste water management systems. Agriculture was the main economic activity of the society and an extensive network of reservoirs, wells, canals along with low cost water harvesting techniques were developed throughout the region at that time (Nair, 2004). The Mohenjo-Daro and Dholavira, major cities of Indus Valley are the best examples having the state-of-the art water management and drainage systems. The Great Bath of Mohenjo-Daro of Indus Valley is considered as the "earliest public water tank of the ancient world". The "*Arthashastra*" attributed to Kautilya "who reportedly was the chief minister to the emperor Chandragupta (300 BC), the founder of the Mauryan dynasty" (Encyclopaedia Britannica, https://www.britannica.com/topic/Artha-shastra) deals with several issues of governance, including water governance. It mentions about a manually operated cooling device "Variyantra" (revolving water spray for cooling the air). It also gives an extensive account of hydraulic structures built for irrigation and other purposes during the period of the Mauryan empire (Shamasastry, 1961).

The Pynes and *Ahars* (combined irrigation and water management system), reservoir (Sudarshan lake) at Girnar and many other structures were also built during the Mauryan empire (322-185 BC). McClellan III and Dorn, (2015) noted that '… the Mauryan empire was first and foremost a great hydraulic civilization …'. This reflects that the technology of the construction of the dams, reservoirs, channels, measurement of rainfall and knowledge of the various hydrological process was well known to the ancient Indian society. The water pricing was also an important component of the water management system in Mauryan empire. There are also adequate archaeological evidences to testify that the Harappans of the Indus Valley were well aware of the seasonal rainfall and flooding of the river Indus during the period between 2500 and 1700 B.C., which is corroborated by modern meteorological investigations (Srinivasan, 1976).

The Vedic texts, which were composed probably between 1500 and 1200 BC (1700–1100 BC according to some scholars), contain valuable references to 'hydrological cycle'. It was known during Vedic and later times (Rigveda, VIII, 6.19, VIII, 6.20; and VIII, 12.3) (Sarasvati, 2009) that water is not lost in the various processes of hydrological cycle namely evaporation, condensation, rainfall, streamflow, etc., but gets converted from one form to another. Indians were, at that time, acquainted with cyclonic and orographic effects on rainfall (*Vayu Purana*) and radiation, and convectional heating of earth and evapotranspiration. The Vedic texts and other Mauryan period texts such as '*Arthshastra*' mention about other hydrologic processes such as infiltration, interception, streamflow and geomorphology, including the erosion process. Reference to the hydrologic cycle and artesian wells is available in *Ramayana* (200 B.C.) (Vālmīki and Goswami, 1973). Ground water development and water quality considerations also received sufficient attention in ancient India, as evident from the *Brihat Samhita* (550 A.D.) (Jha, 1988). Topics such as water uptake by plants, evaporation, clouds and their characteristics along with rainfall prediction by observing the natural phenomena of previous years, had been discussed in *Brihat Samhita* (550 A.D.), *Meghamala* (900 A.D.) and other literature from ancient India.

Historical development of hydro-science has been dealt by many researchers (Baker and Horton, 1936; Biswas, 1969; Chow, 1964). However, not many references to the hydrological contributions in ancient India are found. Chow (1974) rightly mentions that "… the history of hydrology in Asia is fragmentary at best and much insight could be obtained by further study". According to Mujumdar and Jain (2018), there is rigorous discussion in ancient Indian literature on several aspects of hydrologic processes and water resources development and management practices as we understand them today.

Evidences from ancient water history provide an insight into the hydrological knowledge generated by Indians more than 3000 years ago. This paper explores the many facets of ancient Indian knowledge on hydrology and water resources with focus on various hydrological processes, water management and technology, and wastewater management, based on earlier reviews of Indian scriptures such as the Vedas, the *Arthasastra* (Shamasastry, 1961), *Astadhyayi* (Jigyasu, 1979), *Ramayana* (Vālmīki and Goswami, 1973), *Mahabharata*, *Puranas*, *Brihat Samhita* (Jha, 1988), *Meghmala*, *Mayurchitraka*, Jain and Buddhist texts and other ancient texts.

2 Knowledge of Hydrological Processes in Ancient India

Hydrologic cycle is the most fundamental concept in hydrology that involves the total earth system comprising the atmosphere (the gaseous envelop), the hydrosphere (surface and subsurface water), lithosphere (soils and rocks), the biosphere (plants and animals), and the Oceans. Water passes through these five spheres of the earth system in one or more of the three phases: solid (ice), liquid and vapour. The *Rigveda*, which is an ancient religious scripture, contains many references to hydrologic cycle and associated processes (Sarasvati, 2009). The *Rigveda* mentions that 'the God has created Sun and placed it in such a position that it illuminates the whole universe and extracts water continuously (in the form of vapour) and then converts it to cloud and ultimately discharges as rain' (Verse, I, 7.3). Many other verses of the *Rigveda* (I, 19.7; I, 23.17; I, 32.9) further explain the transfer of water from earth to the atmosphere by the Sun and wind; breaking up of water into small particles and evaporation due to Sun rays and subsequent rain; formation of cloud due to evaporation of water from the mother Earth and returning in the form of rain. The verse I, 32.10 of the *Rigveda* further mentions that the water is never stationary but it continuously gets evaporated and due to smallness of particles we cannot see the evaporated water particles. According to *Atharvaveda* also (1200-1000 B.C.), the Sun rays are the main cause of rain and evaporation (Verse, I, 5.2, in Sanskrit language):

amurya up surye yabhirg suryah sah| ta no hinvantvadhavaram||

The *Yajurveda* (1200 – 1000 BC) explains the process of water movement from clouds to Earth and its flow through channels and storage into oceans and further evaporation (Verse, X, 19). During the time of *Atharvaveda*, the concept of water evaporation, condensation, rainfall, river flow and storage and again repetition of cycle was

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also well known as in the earlier Vedas. Therefore, it can be inferred that during the Vedic and earlier periods in India, the concepts of infiltration, water movement, storage and evaporation as the part of hydrologic cycle were well known to the contemporary Indian scholars.

The epic *Mahabharata* (Verse, XII,184.15-16) explains the water uptake process by plants and mentions that rainfall occurs in four months (the Indian summer monsoon, ISM) (Verse, XII,362.4-5) and in the next eight months (non-monsoon months), the same water is extracted by the Sun rays through the process of evaporation. Likewise, in other Indian mythological scriptures such as *Puranas* (which are dated probably between 600 B.C. to 700 A.D.), numerous references exist to hydrological cycle (NIH, 2018). The *Matsya Purana* (Verse, I, 54.29-34) and *Vayu Purana* (Verse, 51.23-26) mention about the evaporation process which burns water by Sun rays and is converted to smoke (i.e., process of evaporation) which ascend to atmosphere with the help of air and again rains in next rainy season for the goodness of the living beings (NIH, 2018). The *Vayu Purana* and the *Matsya Purana* also mention the rainfall potential of clouds and the formation of clouds by cyclonic, convectional and orographic effects (Nair, 2004). Similarly, the *Linga Purana* (Verse, I, 36.67) clearly explains the various processes of hydrologic cycle such as evaporation, condensation and mentions that water can't be destroyed; it gets changed from one form to the other (NIH, 2018; Sharma and Shruthi, 2017) as:

jalasya nasho vridwirva natatyevasya vichartah| ghravenashrishthto vayuvrishti sanhrte punah||

The *Brahmanda Purana* (Verse, II, 9.138-139; 167-168) explains that Sun has rays of seven colors which extracts water from all sources through heating (evaporation) and it gives to the formation of clouds of different colors and shapes and finally these clouds rain with high intensity and great noise (NIH, 2018). The *Vayu Purana* also refers to the various underground structures and topography such as lakes, barren tracts, dales, rocky rift valley between mountains (Verse, 38.36).

The *Kishkindha sarga* (Chapter 28; Verses: 03, 07, 22, 27, 46) of the epic *Ramayana* discusses various aspects of hydrological cycle. The verse 3 mentions about the formation of clouds by Sun and wind (through process of evaporation from sea) and raining the elixir of life (water) and verse 46 mentions the overflowing of the rivers due to heavy rains in rainy season. The verse 22 explains the process of cloud transportation laden with water and elevational effects of the mountains on the whole processes. Based on these verses (and many more, not mentioned here) a depiction on the various stages of the hydrologic cycle may also be established similar to Horton (1931). Malik (2016) also compared the various concepts of modern hydrologic cycle with those presented in the Ramayana and found that a corollary may be established between them.

The *Brihat Samhita* (literally meaning *big collection*) (550 A.D.) by Varahamihira, contains many scientific discourses on the various aspects of meteorology, e.g., pregnancy of clouds, pregnancy of air, winds, cloud formations, earthquakes, rainbows, dust storms and thunder bolts among other things such as colours of the sky, shapes of clouds, the growth of vegetation, behaviour of animals, the nature of lightning and thunder and associated rainfall patterns (Jha, 1988). The water falling from sky assumes various colours and tastes from differences in the nature of Earth. Out of 33 chapters in the *Brihat Samhita*, 10 chapters are specifically devoted to the meteorology. This highlights the depth of the meteorological knowledge prevalent during the period of Varahmihira and his predecessors in the ancient India.

The verse 54.104 of *Brihat Samhita* explains the relation between soil and water. It is mentioned that pebbly and sandy soil of copper color makes water astringent. Brown-colored soil gives rise to alkaline water, yellowish soil makes water briny and in blue soil, underground water becomes pure and fresh. *Brihat Samhita* also discusses about the geographical pointers such as plants, reptiles, insects as well as soil markers to gauge the groundwater resources (occurrence and distribution) (Chapter 55, Dakargalam). It explains the groundwater recharge as "… the water veins beneath the earth are like vein's in the human body, some higher and some lower..." as given in the following verses (NIH, 2018):

Dharmyam yashashyam va vadabhaytoham dakargalam yen jaloplabdhiha
Punsam yathagdeshu shirastathaiva chhitavapi pronnatnimnasanstha.

Ekayna vardayna rasayna chambhyashchyutam namasto vasudha vishayshanta
Nana rastvam bahuvarnatam cha gatam pareekshyam chhititulyamayva.

The 'Dakargalam' (*Brihat Samhita*, Chapter 55) deals with ground water exploration and exploitation with various surface features, that are used as bio indicators to locate sources of ground water, at depths varying from 2.29 m to as much as 171.45 m (Prasad, 1980). The bio indicators, described in this ancient Sanskrit work, include various plant species, their morphologic and physiographic features, termite mounds, geophysical characteristics, soils and rocks (Prasad, 1986). All these indicators are nothing but the conspicuous responses to biological and geological materials in a microenvironment, consequential to high relative humidity in a ground water ecosystem, developed in an arid or semi-arid region. Variation in the height of water table with place, hot and cold springs, groundwater utilization by means of wells, well construction methods and equipment are fully described in the Dakargalam (Jain et al. 2007). It also means that the water which falls from the sky originally has the same colour and same taste, but assumes different colour and taste after falling on the surface of Earth and after percolation.

Glucklich, (2008) opines about the *Brihat Samhita*: "… as the name of the work itself indicates, its data came from numerous sources, some of them probably quite old. However, the prestige and systematic nature of the *Brihat Samhita* gave its material the authority of prescriptions". Further, it is also appropriate to quote Varahmihira (Chapter 1, Verse, II, Brihat Samhita) that '… having correctly examined the substance of the voluminous works of the sages of the past, I attempt to write a clear treatise neither too long nor too short …' (Iyer, 1884).

An interesting fact covered in details by Varahamihira is the role of termite knolls as indicator of underground water. Apart from the underground water exploration, some of the verses of the chapter deal with topics such as digging of wells, their alignment with reference to the prevailing winds, dealing with hard refractory stony strata, sharpening and tempering of stone-breaking chisels and their heat treatment, treating with herbs of water with objectionable taste, smell, protection of banks with timbering and stoning and planting with trees, and such other related matters.

The Jain literature also made considerable contribution in the field of meteorology. The '*Prajnapana*' and '*Avasyaka Curnis*' provide outstanding references to the various types of winds (Tripathi, 1969). The *Avasyaka Curnis* furnishes a list of fifteen types of winds and the '*Prajanapana*' also mentions the snowfall and hailstorm as form of the precipitation. The Buddhist literature also throws significant light on meteorology. In the narrative of the first Jataka, named '*Apannaka*', several climatological facts are described therein. The Buddhist literature refers to two general classes of clouds as: monsoon cloud and storm clouds or accidental ones (Tripathi, 1969). The *Samyutta Nikaya* classifies clouds into five categories as (i) cool clouds, (ii) hot clouds, (iii) thunder clouds, (iv) wind clouds –formed due to the activity of convection current in the atmosphere, and (v) rain clouds – most probably cumulonimbus which brings copious downpour of rain.

3 Measurement of Precipitation

The "*Arthashastra*" and "*Astadhyayi*" of Panini (700 B.C.) mention about the rain gauges (Nair, 2004), which was introduced by the Mauryan rulers in the *Magadha* country (south Bihar) in the fourth or third century B.C. They are also credited with the establishment of first observatory. The system continued to be used by the succeeding rulers until the end of the sixth century A.D. (Srinivasan, 1976). During the Mauryan period, the raingauge was known as "*Varshamaan*". In the Arthshastra, the construction of the raingauge is described as "… in front of the store house, a bowel (Kunda) with its mouth as wide as an aratni (24 *angulas* = 18" nearly) shall be set up as raingague". However, the '*Arthshastra*' does not have any information about the height of the raingauge (Srinivasan, 1976). This rainguage continued to be employed effectively by the succeeding rulers until the end of the 600 A.D (Srinivasan, 1976; Murty, 1987). A schematic of the modern raingauge is shown in Figure 1. By comparing the dimensions of the ancient Indian and Symon's raingauge, one can infer about the advanced level of knowledge possessed during that period.

The distribution of rainfall in various regions was well known during the Mauryan period. The '*Arthshastra*' mentions as: "'The quantity of rain that falls in the country of *jangiila* (desert regions or regions full of jungles) is 16 *dronas;* half as much more in *anupanam* (moist regions); as the regions which are fit for agriculture *(desavapanam)*; 13.5 dronas in the regions of *asmakas* (Maharashtra); 23 *dronas* in Avanti (probably Malwa); and an immense quantity in *aparantanam* (western regions, the area of Konkan); the borders of Himalayas and the countries where water-channels are made use of in agriculture". Kautilya's method of classification of rainfall areas in relation to the annual average quantity is indeed remarkable and he is the only classical author who treats this aspect in a nutshell covering almost the whole of the Indian subcontinent (Srinivasan, 1976). From this, it is evident that the methodology of measurement of rainfall given in *Arthshastra* is same as we have today, the only difference is that rain was expressed in weight units. Discussing on the further geographical details of rainfall variation, it is mentioned therein that "…when one third of the requisite quantity of the rainfalls, both during the commencement and closing months of the rainy season, and two third in the middle, then the rainfall is considered very even…".

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The science of forecasting the rains had also come into existence as and must have been developing empirically. It is further mentioned in the '*Arthshastra*' that "the rainfall *forecasting can be made by observing the position, motion and pregnancy (garbhadhan) of Jupitar, the rising, setting and motion of Venus, and the natural or unnatural aspects of the Sun. From the movement of Venus, rainfall can be inferred".* Detailed descriptions on classification of clouds and their water holding capacity (equivalent to the concept of atmospheric rivers) and interrelationship of rainfall patterns and agriculture can also be found in the '*Arthshastra*'.

Therefore, it can be concluded that during the Vedic era and afterwards in the age of epics and *Puranas,* (i.e., from 3000 B.C. to 500 A.D.), the knowledge of hydrologic cycle, ground water and water quality was highly advanced, although the people of those times were solely dependent upon their experience of nature, without sophisticated instruments of modern times. In the Vedic age, Indians had developed the concept that water gets divided into minute particles due to the effect of Sun rays and wind, which ascends to the atmosphere by the capillary of air and there, it gets condensed and subsequently falls as rainfall (*Vayu Purana*, 51. 14-15-16). The *Linga Purana* also details on the various aspects of hydrological cycle (Sharma and Shruthi, 2017). Month wise change in the facets of hydrological cycle was also known. Water uptake by plants which gets facilitated by the conjunction of air along with the knowledge of infiltration is revealed in the ancient literature. In *Brihat Samhita*, a separate chapter is devoted to the formation of clouds (*Garbhalakshanam*). A detail discussion has been given on the properties of rainy seasons and their relationship with the movement of the planest and cloud formations (Murthy, 1987). The *Brihat Samhita* also details on the measurement of rainfall and the dimensions of the raingauge (Murty, 1987).

During the Mauryan period, it was possible to describe the distribution of rainfall in different areas of India. Mauryans are credited with the installation of first observatory worldwide (Srinivasan, 1976). Modern meteorological facts like arid region of Tibetan rain shadow area and no rainfall due to polar winds are fully covered in *Puranas*. The Jain and Buddhist works guessed the actual height of clouds. Knowledge of monsoon winds (Tripathi, 1969) and their effects as conceived by ancient Indians (*Brihat Samhita*) is in accordance to modern hydro-science. These facts show that there was enriched knowledge of water science and associated processes, including meteorology during ancient times in India, which is at par to the modern water science.

Well before many centuries of Christ, ancient Indians were aware of underground water bearing structures, change in the direction of flow of ground water, high and low water tables at different places, hot and cold springs, ground water utilization by means of wells, well construction methods and equipment, underground water quality and even the artesian well schemes. This shows that well developed concepts of hydrological cycle, groundwater and water quality were known to the ancient Indians in those ancient times while the contemporary world was relying on the wild theories of origin and distribution of water.

4 Water Management Technology in Ancient India

The development of socio-cultural societies, agricultural establishments and permanent settlements led to the establishment of a unique relationship between humans and water (Vuorinen et al., 2007; Lofrano and Brown, 2010). Scarborough (2003) and Ortloff (2009) discussed the impacts of water management practices on ancient social structures and organizations with examples of the Eastern and Western hemispheres. Lofrano and Brown,

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(2010) presented an in-depth review of wastewater management in the history of mankind. In this review work they have categorically discussed about the evolution of sanitation through different civilizations of the world, including the ancient Indus civilization).

During the Vedic age, the principle of collecting water from hilly areas of undulating surface and carrying it through canals to distant areas was known (Bhattacharya, 2012). In the *Rigveda*, many verses indicate that the agriculture can be progressed by use of water from wells, ponds (Verse, I, 23.18 and Verse, V, 32.2). Verse (VIII, 3.10) mentions construction of artificial canals by (Ribhus/Engineer) to irrigate desert areas. Verses (VIII, 49.6 and X, 64.9) emphasizes for efficient use of water, i.e., the water obtained from different sources such as wells, rivers, rain and from any other sources on the earth should be used efficiently, as it is a gift of nature, for well-being of all. There are also references of irrigation by wells (Verse, X. 25), canals (word '*kulya*' in *Rigveda*) (Verse, X.99), and digging of the canal (Verse, X75) in the Rigveda. In *Mahâbhâsya* of Patañjali (150 B.C.) the word '*kulya*' is also used.

Interestingly, the *Rigveda* (Verses, X 93.12; X 101.7) has a mention of 'asmacakra' (a wheel made of stones) and water was raised with help of wheel in a pail using a leather strap. There is also a mention of '*Ghatayantra*' or '*Udghatana*' (a drum-shaped wheel) round which a pair of endless ropes with ghata (i.e. earthen pots) tied at equal distances. In Arabic literature, the water lifting wheel is also known as 'Noria'. Yannopoulos et al., (2015) also mentioned that the ancient Indians had already developed water lifting and transportation devices. Further, according to Joseph Needham (https://www.machinerylubrication.com/Read/1294/noria-history), due to evidence documented in Indian texts dating from around 350 B.C., the 'Noria' was developed in India around the fifth or fourth century B.C and transmitted to the west by the first century B.C. and to the China by the second century A.D.

Similar to *Rigveda*, *Yajurveda* also contains references on water management. Verses VI, 100.2 and VII,11.1 mention "…that the learned men bring water to desert areas by means of well, pond, canals etc….and the man should think about the drought, flood and like natural calamities in advance and take preventive measures accordingly. Verse (XII,1.3) of *Atharvaveda* mentions that those who use rainwater by means of rivers, wells, canals for navigation, recreation, agriculture etc., prosper all the time. Similarly, verse (XX, 77.8) of the *Atharvaveda* directs the king to construct suitable canals across mountains to provide water for his 'subject' for agriculture other purposes. The *Yajurveda* also has references, directing the man to use rain and river water by means of wells, ponds, dams and distribute it to various places having need of water for agriculture and other purposes. The *Atharvaveda* talks about the drought management through efficient use of available water resources and emphasizes, these waters are used efficiently, will reduce the intensity of droughts. Verse (2.3.1) of the *Atharvaveda* instructs for proper management of various water bodies such as brooks, wells, pools and an efficient use of their waters resources for reducing the droughts intensity and water scarcity (Sharma and Shruthi, 2017).

As in many other parts of the World, civilization in India also flourished around rivers and deltas. Rivers remain an enduring symbol of national culture (Nair, 2004). The Harappan (or Indus Valley) Civilization (Figure 2) which prospered during 2600–1900 B.C. (Chase et al., 2014) or about 5000 years ago (Dixit et al., 2018) had well

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planned cities equipped with the public and private baths, well planned network of sewerage systems through underground drains built with precisely laid bricks, and an efficient water management system with numerous reservoirs and wells (Sharma and Shruthi, 2017). Evidences show that the Indus people developed one of the smartest urban centres in those old times with exemplary fusion of civil, architectural and material sciences (Possehl, 2002; Kenoyer, 1998; Wright, 2010). According to Shaw et al., (2007), the development of advanced irrigation systems in ancient India led to the development of the complex urban societies and centres. The Indus civilization was prominent in hydraulic engineering is known to have earliest known systems of flush toilets in the world (Sharma and Shruthi, 2017). Kenoyer (2003) states that "… no other city in the ancient world had developed such a sophisticated water and waste management system. Even during the Roman Empire, some 2,000 years later, these kinds of facilities were limited to upper-class neighbourhoods".

The Dholavira, an important city in the Indus civilization, contained sophisticated water management systems comprising series of reservoirs, step wells and channels (Kirk, 1975; Sharma and Shruthi, 2017; Wright, 2010) (Figures 3a and Figure 3b). The city is ringed with a series of 16 large reservoirs (7 m deep and 79 m long), some of them interconnected and together, these storage structures account for about 10% of the area of the city (Iyer, 2019). The ability to conserve every drop of water in the parched landscape speaks volumes about the engineering skills of the people of Dholavira. Recently, a rectangular stepwell has also been found at Dholavira which measured 73.4 m long, 29.3 m wide, and 10 m deep, making it three times bigger than the Great Bath of Mohenjo-Daro (https://www.secret-bases.co.uk/wiki/Dholavira).

The systems that Harappans of Dholavira city developed for conservation, harvesting, and storage of water, speak eloquently about their advanced hydraulic engineering capabilities, given the state of technology (Baba et al., 2018). The "Lothal" ("meaning *Mound of the dead*"), known as the harbour city of the Harappan civilization (Bindra, 2003), is located at the *doab* of the Sabarmati and Bhogavo rivers. A roughly trapezoidal structure having dimensions of 212.40 m on the western embankment, 209.30 m on the eastern one, 34.70 m on the southern one and 36.70 m on the northern one (Rao, 1979) at Lothal is an example of advanced maritime activities in those old days and is claimed by the archeologists to be the first known dockyard of the world (Nigam, 2016). Figure 4a and Figure 4b show the dockyard at the Lothal after rains and the ancient Lothal as envisaged by the Archaeological Survey of India (ASI). According to Nigam et al. (2016), the existence of the massive protective wall (thickness up to 18 m) around the Dholavira city indicates the ancient Indians were aware of oceanic calamities such as Tsunami/storm.

Agriculture was practised on a large scale having extensive networks of canals for irrigation (Nair, 2004). The irrigation systems, different types of wells, water storage systems and low cost and sustainable water harvesting techniques were developed throughout the region at that time (Nair, 2004; Wright, 2010). Mohenjo-Daro was one of the major urban centres of the Harappan civilization receiving water from at least 700 wells and almost all houses had one private well (Angelakis and Zheng, 2015). The wells were designed as circular to *pipal* (Ficus religiosa) leaf shaped (Khan 2014). Canalising flood waters through ditches for irrigating the Rabi crops (crops of the dry season) was also practiced at that time (Wright, 2010). The farmers of Harappa frequently used "contouring, bunding, terracing, benching, *gabarbands* (dams) and canals for water management (Mckean, 1985).

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The Gabarbands (stone-built dams for storing and controlling water) were also prevalent in these times for irrigating agricultural lands during the dry seasons (Rabi crops) (Wright, 2010).

Agriculture and livestock rearing occupied a prominent role during Jainism and Buddhism period (600 B.C.) and channel irrigation was in vogue (Bagchi and Bagchi, 1991). Field embankments were constructed surrounding the fields to increase water holding capacity at strategic points with sluice gates to harness river water with proper regulation facilities (*Arthshastra*, 400 B.C.) and irrigation through conduits was in practice to deliver water to the irrigation field for attaining higher efficiency (Bagchi and Bagchi, 1991). Literature suggests that a large number of hydraulic structures (dams, canals and lakes) were built during the Mauryan period in Indo-Gangetic plains and other parts of the country for irrigation and drinking purposes (Shaw et al., 2007; Sutcliffe et al., 2011). Surprisingly, many of these structures were equipped with the spillways to consider the flood protection measures. During the Mauryan empire (400 BC-184 B.C), emperor Chandragupta Maurya constructed Sudarsana dam in Girnar, Junagadh, Gujarat. Subsequent structural improvements involve the addition of conduits during the reign of Asoka the Great, by his provincial governor the "Yavana Administrator (Greek Administrator)", Tusaspha (Kielhorn, 1906; Shaw and Sutcliffe, 2001). In an excavation work conducted by Archaeological Survey of India (ASI) during 1951-55, in Kumhrar (the site of ancient Pataliputra) a few miles south of Patna, Bihar "a canal 45 feet broad 10 feet deep and traced up to the length of 450 feet" was found of the Mauryan period. The canal was linked with the 'Sone river' and also with the 'Ganges' for navigation purposes and also for the need of irrigation to that area (Bhattacharya, 2012).

Here, it is instructive to quote Bhattacharya, (2012) : "… by the beginning of 300 B.C., a firm administrative set up had taken shape. As a recognition of high position accorded to agriculture by the rulers as well as the people at large, the construction of tanks and other types of reservoirs was considered to be an act of religious merit. The king with the help and advice of his tiers of officials, ministers, consultants started acting as the "Chief trustee" for optimizing, rationalizing and overall management of water resources. The *Arthasastra* of Kautilya gives us an idea of principles and methods of management of irrigation systems … that the Mauryan kings took keen interest in the irrigation schemes, is borne at by the report of Megasthenes (a Greek traveller) who mentions about a group of officers responsible for superintending the rivers, measuring the land as is done in Egypt and inspecting the sluices through which the water is released from the main canals into their branches so that everyone may have an equal supply ...".

Shaw and Sutcliffe, (2001) presented hydrological background of the historical development of water resources in South Asia with particular emphasis on ancient Indian irrigation system at the Sanchi site (a well-known Buddhist site and a UNESCO World Heritage site located in Madhya Pradesh). They investigated a 16-reservoir complex located in in the Betwa river sub-basin (a tributary of Yamuna in Ganga basin) in Madhya Pradesh, India during 1998 and 2005 (Shaw, 2000; Shaw et al., 2007; Shaw and Sutcliffe, 2001, 2003a&b, 2005). In addition to Sanchi, four other known Buddhist sites of Morel-khurd, Sonari, Satdhara and Andher, all established between 300-200 B.C. (Cunningham, 1854; Marshall, 1940) were also surveyed by them. The heights of the dams were found to vary from 1 to 6 m and their lengths from 80 to 1400 m with flat downstream faces; presumably designed to reduce damage from overtopping. At least two of the larger dams were equipped with spillways, which could

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pass floods of about 50 years' return period and it suggests that flood protection was also taken into account while designing these structures (Shaw and Sutcliffe, 2003a). Their reservoir volumes range from 0.03 to 4.7×10^6 m^3 and these estimates are closely related to the runoff generated by their catchments based on the present hydrological conditions. These dams were constructed to a height sufficient to ensure that the reservoir volume would be closely related to the volume of runoff from the upstream catchment of each site (Shaw and Sutcliffe, 2001). This indicates that these structures would have been constructed based on the detailed hydrological investigations of the region. More or less identical spillways were also found with a group of much smaller reservoirs in the neighbouring Devnimori area of Gujarat (Mehta, 1963). There are close similarities between the Sanchi dams and well known Sudarsana dam (Shaw and Sutcliffe, 2003b). Sutcliffe et al., (2011) opines that it is likely that some of the larger dams in the Sanchi area may have been fitted with similar spillways, which have subsequently been obscured by siltation or erosion.

According to Shaw and Sutcliffe, (2001), a close relationship between runoff and reservoir volume in the Sanchi area suggests a high level of understanding of water balance based on considerable period of observation and understandings of local conditions. While excavating the area around the 'Heliodorus' pillar in Vedisa (present day Vidisha, Madhya Pradesh), Bhandarkar, (1914) found the remains of a 300 B.C. canal, which would have been drawing water from the river Betwa. However, Shaw and Sutcliffe, (2001) further mentions that a more comprehensive understanding of ancient Indian irrigation would have been developed; had adequate attention been paid to the Sanchi reservoir complex during the Vedisa excavations. Based on these findings, Shaw and Sutcliffe (2003a&b) and Sutcliffe et al. (2011) conclude that the Sanchi Dam system would have been built on the basis of a sound knowledge of the principles of water balance with detailed hydrological investigations and by 'engineers with experience of reservoir irrigation' with a higher level understanding of the hydraulic technology.

During the Sangam Period (300 B.C. to 300 A.D.), in the southern parts of India, the rainwater harvesting structures such as tanks (*ery* in Tamil) were constructed for irrigating the paddy fields (Fardin et al., 2013; Sita, 2000) and fishing was also practiced in lotus ponds (*tamaraikulam* in Tamil) (Sita, 2000). The Grand Anicut (Kallanai Dam) was constructed by the Chola King Karikalan during the 1st century A.D. on the river Cauvery for protection of the downstream populations against flood and to provide for irrigation supplies in the Cauvery delta region. The Grand Anicut is the world's oldest still in use dam and is also credited with being the 4th oldest dam in the world and the first in India. In *Brihat Samhita* (550 A.D.), there are references regarding the orientation of ponds, bank protection through pitching, plantation and also by providing sluicing arrangements. *Brihat Samhita* contains many references regarding the orientation of ponds so as to store and conserve water efficiently (reducing evaporation losses), plantation type for bank protection and proper sluicing to protect pond/reservoir from any possible damage. Verse (54.118) mentions that a pond oriented in east to west direction retains water for a long time while one from north to south loses invariably by the waves raised by the winds. Verse (54.120) suggests for construction of spillway as an outlet for the water should be made on a side with the passage being laid with stones.

5 Wastewater Management in Ancient India

The sanitation and wastewater management has always been one of the most important socio-environmental challenges that the humankind has ever faced and the societies in the ancient India had developed stat-of-the art technological solutions by utilizing their knowledge on hydraulic systems with the structural and materials advancements. Apart from the detailed references on various aspects of hydrology as discussed earlier, we also get some references to water quality in Vedas and other early literature, especially in *Atharvaveda, Charaka Samhita*, and *Susruta Samhita* (both of pre- or early Buddhist era) (NIH, 2018). There are hymns in *Rigveda* stating the role of forest conservation and tree plantation on water quality (Verse V, 83.4). The Verse V, 22.5 of *Atharvaveda*, cautioned people from diseases living in a region with heavy rainfall and bad quality of water. There are instances of classifying water based on taste in epic *Mahabharata* (Verse XII, 184.31 & 224.42). The *Brihat Samhita* also discussed the relationship between soil colour and water quality (Verse, 54.104) and techniques are mentioned for obtaining potable water with medicinal properties from contaminated water (Verses 54.121 & 54.122).

The Harappan cities were one of the very first and most urbanised centres developed with the excellent civil and architectural knowledge in the old world. Even as early as 2500 BCE, Harappa and Mohenjo-Daro included the world's first urban sanitation systems (Webster, 1962). The water and wastewater management systems have been highly amenable to the socio-cultural and socio-economic conditions and religious ways of societies through all the ages of the civilizations (Sorcinelli, 1998; Wolfe, 1999; De Feo and Napoli, 2007; Lofrano and Brown, 2010). All through the ages, the wastewater management has been considered filthy (Lofrano and Brown, 2010; Maneglier, 1994), The evolution process of wastewater management through the ages has been discussed by several researchers worldwide, (e.g., Maneglier, 1994; Serneri, 2007; Sorcinelli, 1998; Sori, 2001; Tarr, 1985; Viale, 2000). Recently, Lofrano and Brown, (2010) presented an in-depth review of wastewater management in the history of mankind and found that the 'Indus civilization was the first to have proper wastewater treatment systems' in those ancient times. Wastewater management and sanitation were the major characteristics of the first urban sites of the Harappan civilisation (Kenoyer, 1991). The sewage and drainage systems were composed of complex networks, especially in Mohenjo-Daro and Harappa (Jansen, 1989). Latrines, soak-pits, cesspools, pipes and channels were the main elements of wastewater disposal (Fardin et al., 2013).

All the houses were connected to the drainage channels covered with bricks and cut stones and the household wastewater was first collected through tapered terra-cotta pipes into the small sumps for sedimentation and removal of larger contaminants (primary wastewater treatment) and then into drainage channels in the street. This most likely was the first attempt at treatment on record (Lofrano and Brown, 2010). These drainage channels were having the provision of cleaning and maintenance by removing the bricks and cut stones (Wolfe, 1999). The cesspits were fitted at the junction of the several drains to avoid the clogging of the drainage systems (Wright, 2010). Fardin et al., (2013) mention that almost all the settlements of Mohenjo-Daro were connected to the drain network. However, at the same time, at Kalibangan, toilets and bathrooms outflows were connected in U-shaped channels made of wood or terracotta bricks with decentralised sewage systems. These effluents poured into a jar placed in the main street (Chakrabarti, 1995). The same model of wastewater collection was used in Banawali, where effluents were channelled into drains made of clay bricks, before reaching the jars (Bisht, 1984).

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In many other parts of the ancient India, e.g., Jorwe (Maharashtra), a similar drainage system was established during 1375–1050 BC (Fardin et al., 2013; Kirk, 1975); at around 500 B.C., the city of Ujjain was also laid down with the sophisticated drainage system having soak-pits built of pottery-ring or pierced pots (Kirk, 1975; Mate, 1969) and in Taxila around 300 B.C. very muh similar drainage system to that of Mohenjo-Daro was in place. (Singh, 2009). This shows that during the ancient times, modern concepts of sanitation and waste water management technology were very well known to the Indians and were in their advanced stages during the Indus valley civilization and later periods. Modern methods of wastewater disposal systems based on centralized and decentralized concept as well as methods for wastewater treatments during Indus valley civilization were even better than those used in the contemporary world.

6 Summary and Conclusions

This paper has explored the hydrological developments in ancient India starting from Harappa Civilization to the Vedic Era and later, using references from Vedas, mythological epics such as *Mahabharata*, *Ramayana*, Jain and Buddhist literature, and the references of *Arthshastra*, Astadhyayi and many other Vedic text such as Puranas (*Brahmana*, *Linga*, etc.), *Brihat Samhita*, and other ancient literature. The following conclusions can be drawn from this exploration:

1. The Vedas, particularly the *Rigveda*, *Atharvaveda* and *Yajurveda* had specifically dwelt upon the hydrologic cycle and various associated processes. The concepts of evaporation, cloud formation, water movement, infiltration and river flow and repetition of cycle are explicitly discussed in these ancient texts. *Ramayana* has also mentioned about hydrologic cycle and artesian wells. *Mahabharata* explains about the monsoon seasons and water uptake process by plants. Rigveda also mentions about water lifting device such as *Asmacakra/Ghatyanta* (similar to Noria), among others.
2. *Matsya Purana*, *Vayu Purana*, *Linga Purana*, and *Brahmanda Purana* also mention about the processes of evaporation, formation of clouds due to cyclonic, convectional and orographic effects, rainfall potential of clouds and many other associated hydrological processes.

3. The *Rigveda*, *Atharvveda*, *Brihat Samhita*, *Susrutu Samhita* and *Charaka Samhita* have numerous references of water quality and nature-based solutions (NBS) for obtaining potable water. The Dakargalam Chapter of *Brihat Samhita* dwelt upon the occurrence and distribution of groundwater resources using geographical pointers and soil markers.

4. The Harappa Civilization epitomizes the level of development in water sciences. Extensive network of canals, water storage structures, different types of wells, and low cost and sustainable water harvesting structures were developed during this period. These people had created sophisticated water and wastewater management systems, planned network of sewerage systems through underground drains and also had the earliest known system of flush toilets in the world. The Harappa Civilization is also credited with the first known dockyard in the entire world. Indus people were also aware about the oceanic calamities such as Tsunami.

5. The first observatory for measuring rainfall using '*Varshamaan'* (raingauge) was established during Mauryan empire in India. The reservoirs, dams, canals equipped with the spillways were constructed for irrigation and domestic supplies with adequate knowledge of water balance. Some structures were also constructed considering 50 years' return period. In ancient water history, the Mauryan period is also credited with the first and foremost hydraulic civilization. Forecasting of rainfall and water pricing system was also prevalent in this period.

6. The hydrologic knowledge in ancient India was contained in the *shlokas* of scriptures and very few people are conversant with the languages of the scriptures. Hence, the knowledge and wisdom remained largely unknown to the recent generations. Further, the script of the Harappans has not yet been deciphered. If further research is carried out on ancient literature and when the script of the Harappans is deciphered, it is highly likely that many more facts will emerge which may be much more fascinating than what we know so far.

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References

Angelakis, A. N. and Zheng, X. Y.: Evolution of Water Supply, Sanitation, Wastewater, and Stormwater Technologies Globally, Water, 7(2), 455–463, doi:10.3390/w7020455, 2015.

Baba, A., Tsatsanifos, C., El Gohary, F., Palerm, J., Khan, S., Mahmoudian, S. A., Ahmed, A. T., Tayfur, G., Dialynas, Y. G. and Angelakis, A. N.: Developments in water dams and water harvesting systems throughout history in different civilizations, Int. J. Hydrol., 2(2), doi:10.15406/ijh.2018.02.00064, 2018.

Bagchi, K. S. and Bagchi, S. S.: History of Irrigation in India I. Irrigation in Ancient India (From 2295 Bc upto the 11th Century), Irrig. Power J., 48(3), 69–76, 1991.

Baker, M. N. and Horton, R. E.: Historical development of ideas regarding the origin of springs and ground-water, Eos Trans. Am. Geophys. Union, 17(2), 395–400, 1936.

Bhandarkar, D. R.: Excavations at Besnagar, Annual Reports, Archaeological Survey of India., 1914.

Bhattacharya, P. K.: Irrigation and Agriculture In Ancient India. Sectional President's Address, Proc. Indian Hist. Congr., 73, 18–34 [online] Available from: https://www.jstor.org/stable/44156186 (Accessed 27 April 2020), 2012.

Bindra, S. C.: Lothal: A Harappan port town revisited, Purātattva, (33), 1, 2003.

Bisht, R. S.: Structural remains and town planning of Banawali, in Frontiers of the Indus Civilization: Sir Mortimer Wheeler Commemoration Volume, pp. 89–98, Books & Books., 1984.

Biswas, A. K.: History of hydrology, North-Holland Publishing Company, Amsterdam., 1969.

https://doi.org/10.5194/hess-2020-213
Preprint. Discussion started: 11 May 2020

Chakrabarti, D. K.: The archaeology of ancient Indian cities, Oxford University Press, USA., 1995.

Chase, B., Ajithprasad, P., Rajesh, S. V., Patel, A. and Sharma, B.: Materializing Harappan identities: Unity and diversity in the borderlands of the Indus Civilization, J. Anthropol. Archaeol., 35, 63–78, doi:10.1016/j.jaa.2014.04.005, 2014.

Chow, V. T.: Handbook of Applied Hydrology: A Compendium of Water-resources Technology, 1st edition., McGraw-Hill Company, New York, NY., 1964.

Chow, V. T.: Contributions of Asian civilizations to the concept of the hydrological cycle, UNESCO [online] Available from: http://agris.fao.org/agris-search/search.do?recordID=FD7502194 (Accessed 27 April 2020), 1974.

Cunningham, S. A.: The Bhilsa Topes: Or, Buddhist Monuments of Central India, Smith, Elder and Company., 1854.

De Feo, G. and Napoli, R. M. A.: Historical development of the Augustan Aqueduct in Southern Italy: twenty centuries of works from Serino to Naples, Water Supply, 7(1), 131–138, doi:10.2166/ws.2007.015, 2007.

Dixit, Y., Hodell, D. A., Giesche, A., Tandon, S. K., Gázquez, F., Saini, H. S., Skinner, L. C., Mujtaba, S. A. I., Pawar, V., Singh, R. N. and Petrie, C. A.: Intensified summer monsoon and the urbanization of Indus Civilization in northwest India, Sci. Rep., 8(1), 1–8, doi:10.1038/s41598-018-22504-5, 2018.

Fardin, H. F., Hollé, A., Gautier, E. and Haury, J.: Wastewater management techniques from ancient civilizations to modern ages: examples from South Asia, Water Supply, 13(3), 719–726, doi:10.2166/ws.2013.066, 2013.

Glucklich, A.: The Strides of Vishnu: Hindu Culture in Historical Perspective, Oxford University Press, Oxford, New York., 2008.

Horton, R. E.: The field, scope, and status of the science of hydrology, Eos Trans. Am. Geophys. Union, 12(1), 189–202, doi:10.1029/TR012i001p00189-2, 1931.

Iyer, M.: The best laid plans, Deccan Her., 20th January [online] Available from: https://www.deccanherald.com/sunday-herald/best-laid-plans-713650.html (Accessed 27 April 2020), 2019.

Iyer, N. C.: Brihat Samhita of Varaha Mihira, Cent. Secr. Libr. [online] Available from: http://cslrepository.nvli.in//handle/123456789/4675 (Accessed 28 April 2020), 1884.

Jain, S. K., Agarwal, P. K. and Singh, V. P.: Hydrology and Water Resources of India, Springer Science & Business Media., 2007.

Jansen, M.: Water supply and sewage disposal at Mohenjo-Daro, World Archaeol., 21(2), 177–192, doi:10.1080/00438243.1989.9980100, 1989.

Jha, P. A.: Vrhat Sanhita (550 AD) by Varahmihira, Chow Khamba Vidyabhawan., 1988.

Jigyasu, B.: Ashtadhyayi (bhashya) prathamavrtti, three volumes., Ramlal Kapoor Trust Bahalgadh., 1979.

Kenoyer, J. M.: The Indus Valley Tradition of Pakistan and western India, J. World Prehistory, 5(4), 331–385, doi:10.1007/BF00978474, 1991.

Kenoyer, J. M.: Ancient cities of the Indus valley civilization, American Institute of Pakistan Studies., 1998.

Kenoyer, J. M.: Uncovering the keys to the lost Indus cities, Sci. Am., 289(1), 66–75 [online] Available from: https://www.jstor.org/stable/26060364 (Accessed 27 April 2020), 2003.

Khan, S.: Sanitation and wastewater technologies in Harappa/Indus valley civilization (ca. 2600–1900 BC), in Evolution of Sanitation and Wastewater Technologies through the Centuries, vol. 25, IWA Publishing., 2014.

https://doi.org/10.5194/hess-2020-213
Preprint. Discussion started: 11 May 2020

Hydrology and Earth System Sciences
Discussions

Kielhorn, F.: Junagadh rock inscription of Rudradaman: the year 72, Verlag nicht ermittelbar., 1906.

Kirk, W.: The Role of India in the Diffusion of Early Cultures, Geogr. J., 141(1), 19–34, doi:10.2307/1796941, 1975.

Lofrano, G. and Brown, J.: Wastewater management through the ages: A history of mankind, Sci. Total Environ., 408(22), 5254–5264, 2010.

Malik, S.: Conceptual Aspect of Hydrological Cycle in Indian Mythology of Kishkindha Kanda, Ramayana, J. Environ. Earth Sci., 6(4), 54–59 [online] Available from: https://www.iiste.org/Journals/index.php/JEES/article/view/30032 (Accessed 27 April 2020), 2016.

Maneglier, H.: Storia dell'acqua, SugarCo., 1994.

Marshall, S. J. H.: The Monuments of Sanchi, Swati Publications., 1940.

Mate, M. S.: Building in ancient India, World Archaeol., 1(2), 236–246, doi:10.1080/00438243.1969.9979442, 1969.

McClellan III, J. E. and Dorn, H.: Science and Technology in World History: An Introduction, JHU Press., 2015.

Mckean, M. B.: The Palynology of Balakot, a Pre-Harappan and Harappan Age Site in Las Bela, Pakistan., Ph.D Dissertation, Southern Methodist University, Dallas, Texas, USA. [online] Available from: https://elibrary.ru/item.asp?id=7412156 (Accessed 27 April 2020), 1985.

Mehta, R. N.: Ancient bunds in Sabarkantha district, Gujarat, J Orient. Inst. MS Univ. Baroda, 10(4), 359–365, 1963.

Mujumdar, P. P. and Jain, S.K.: Hydrology in Ancient India: Some Fascinating Facets, in EGU General Assembly Conference Abstracts, vol. 20, p. 8690., 2018.

Murty, K. S.: Varahamihira, the Earliest Hydrologist, Water Future Hydrol. Perspect. IAHS Publ., (164), 1987.

Nair, K. S.: Role of water in the development of civilization in India—a review of ancient literature, traditional practices and beliefs, Int. Assoc. Hydrol. Sci., 286, 160–166, 2004.

Nigam, R., Dubey, R., Saraswat, R., Sundaresh, Gaur, A. S. and Loveson, V. J.: Ancient Indians (Harappan settlement) were aware of tsunami/storm protection measures: a new interpretation of thick walls at Dholavira, Gujarat, India, Curr. Sci., 111(12), 2040–2043 [online] Available from: https://www.jstor.org/stable/24911592 (Accessed 27 April 2020), 2016.

NIH: Hydrologic Knowledge in Ancient India, National Institute of Hydrology, Jal Vigyan Bhavan, Roorkee, India., 2018.

Ortloff, C. R.: Water engineering in the ancient world: Archaeological and climate perspectives on societies of ancient South America, the Middle East, and South-East Asia, Oxford University Press., 2009.

Possehl, G. L.: The Indus civilization: a contemporary perspective, Rowman Altamira., 2002.

Prasad, E. A. V.: Ground water in Varahamihira's Vrhat Sanhita. MASSLIT series No. 1, Sri Venkateswara University Press, Tirupathi, India., 1980.

Prasad, E. a. V.: Bioindicators of Ground Water in Varahamihira's Brihat Samhita, Groundwater, 24(6), 824–828, doi:10.1111/j.1745-6584.1986.tb01703.x, 1986.

Raghunath, H. M.: Hydrology: principles, analysis and design, New Age International., 2006.

Rao, S. R.: Lothal—A Harappan Port Town, vol. 1, Mem. Archaeol. Surv. India, (78), 83–84, 1979.

Sarasvati, S. P.: Rig Veda, DAV Publication Division., 2009.

Scarborough, V. L.: The Flow of Power: Ancient Water Systems and Landscapes, 1 edition., School of American Research Press,U.S., Santa Fe, N.M., 2003.

Serneri, S. N.: The Construction of the Modern City and the Management of Water Resources in Italy, 1880—1920, J. Urban Hist., 33(5), 813–827, doi:10.1177/0096144207301452, 2007.

Shamasastry, R.: Kauṭilya's Arthaśāstra, Mysore Printing and Publishing House., 1961.

Sharma, S. and Shruthi, M. S.: Water in Hindu Scriptures: Thank You, Water!, in Water and Scriptures: Ancient Roots for Sustainable Development, edited by K. V. Raju and S. Manasi, pp. 89–172, Springer International Publishing, Cham., 2017.

Shaw, J.: Sanchi and its archaeological landscape: Buddhist monasteries, settlements & irrigation works in Central India, Antiquity, 74(286), 775–776, doi:10.1017/S0003598X00060397, 2000.

Shaw, J. and Sutcliffe, J.: Ancient irrigation works in the Sanchi area: an archaeological and hydrological investigation, South Asian Stud., 17(1), 55–75, doi:10.1080/02666030.2001.9628592, 2001.

Shaw, J. and Sutcliffe, J.: Ancient dams, settlement archaeology and Buddhist propagation in central India: the hydrological background, Hydrol. Sci. J., 48(2), 277–291, doi:10.1623/hysj.48.2.277.44695, 2003a.

Shaw, J. and Sutcliffe, J.: Water Management, Patronage Networks and Religious Change: New evidence from the Sanchi dam complex and counterparts in Gujarat and Sri Lanka, South Asian Stud., 19(1), 73–104, doi:10.1080/02666030.2003.9628622, 2003b.

Shaw, J. and Sutcliffe, J.: Ancient Dams and Buddhist Landscapes in the Sanchi area: New evidence on Irrigation, Land use and Monasticism in Central India, South Asian Stud., 21(1), 1–24, doi:10.1080/02666030.2005.9628641, 2005.

Shaw, J., Sutcliffe, J., Lloyd-Smith, L., Schwenninger, J.-L. and Chauhan, M. S.: Ancient Irrigation and Buddhist History in Central India: Optically Stimulated Luminescence Dates and Pollen Sequences from the Sanchi Dams, Asian Perspect., 46(1), 166–201 [online] Available from: https://www.jstor.org/stable/42928709 (Accessed 27 April 2020), 2007.

Singh, U.: A History of Ancient and Early Medieval India: From the Stone Age to the 12th Century (PB), Pearson Education India., 2009.

Sita, K.: Irrigation system of the Sangam Tamils, in Irrigation system of the Sangam Tamils, pp. 29–36, Rajesh Publications, Nagercoil., 2000.

Sorcinelli, P.: Storia sociale dell'acqua: riti e culture, Pearson Italia Spa., 1998.

Sori, E.: La città ei rifiuti: ecologia urbana dal Medioevo al primo Novecento, Il mulino., 2001.

Srinivasan, T. M.: Measurement of Rainfall in Ancient India, Indian J. Hist. Sci. Calcutta, 11(2), 148–157, 1976.

Sutcliffe, J., Shaw, J. and Brown, E.: Historical water resources in South Asia: the hydrological background, Hydrol. Sci. J., 56(5), 775–788, doi:10.1080/02626667.2011.587425, 2011.

Tarr, J. A.: Historical perspectives on hazardous wastes in the United States, Waste Manag. Res., 3(2), 95–102, doi:10.1016/0734-242X(85)90068-0, 1985.

Tripathi, M. P.: Development of geographic knowledge in ancient India, Varanasi: Bharatiya Vidya Prakashan., 1969.

Vālmīki and Goswami, C.: Śrimad Valmiki-Rāmāyaṇa: with Sanskrit text and English translation, Gita Press., 1973.

https://doi.org/10.5194/hess-2020-213
Preprint. Discussion started: 11 May 2020

Hydrology and Earth System Sciences
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Viale, G.: Un mondo usa e getta. La civiltà dei rifiuti e i rifiuti della civiltà, Feltrinelli Editore., 2000.

Vuorinen, H. S., Juuti, P. S. and Katko, T. S.: History of water and health from ancient civilizations to modern times, Water Supply, 7(1), 49–57, doi:10.2166/ws.2007.006, 2007.

Webster, C.: The Sewers of Mohenjo-Daro, J. Water Pollut. Control Fed., 34(2), 116–123 [online] Available from: https://www.jstor.org/stable/25034575 (Accessed 27 April 2020), 1962.

Wolfe, P.: History of wastewater. World of water 2000–the past, present and future. Water World, Water Wastewater Int. Suppl. Penn Well Mag. Tulsa OH USA, 1999.

Wright, R. P.: The Ancient Indus. Urbanism, Economy and Society in South Asia, Cambridge University Press. [online] Available from: https://nyuscholars.nyu.edu/en/publications/the-ancient-indus-urbanism-economy-and-society-in-south-asia (Accessed 27 April 2020), 2010.

Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A. and Angelakis, A. N.: Evolution of Water Lifting Devices (Pumps) over the Centuries Worldwide, Water, 7(9), 5031–5060, doi:10.3390/w7095031, 2015.

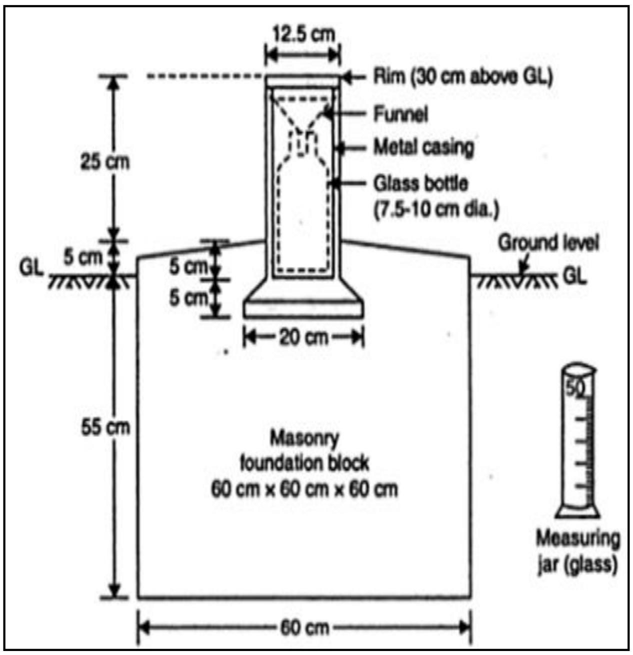

Figure 1: The Symon's raingauge [Source: Raghunath, (2006)].

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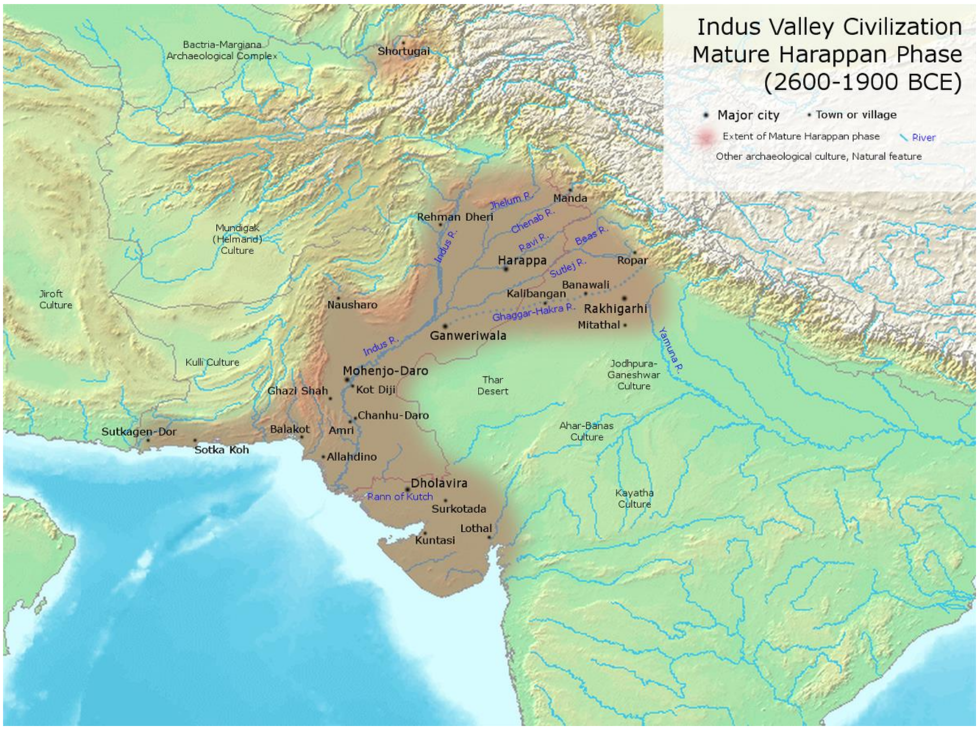

Figure 2: Geographical extent of Indus Valley Civilization [Source: https://commons.wikimedia.org/wiki/File:Indus_Valley_Civilization,_Mature_Phase_(2600-1900_BCE).png].

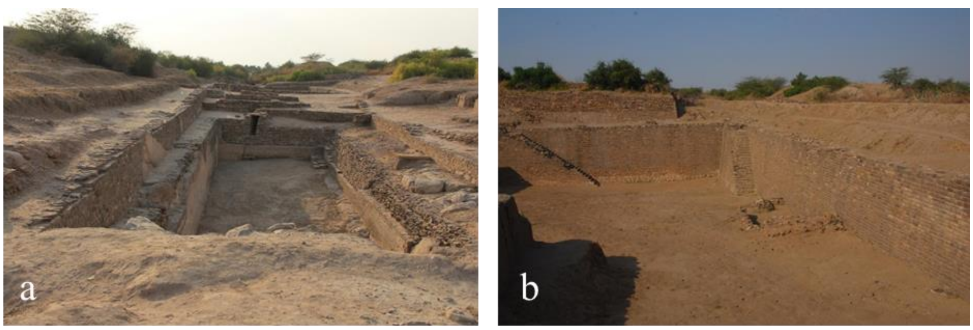

Figure 3: The southern (a) and eastern (b) reservoirs of Dholavira [Source: Iyer, (2019)].

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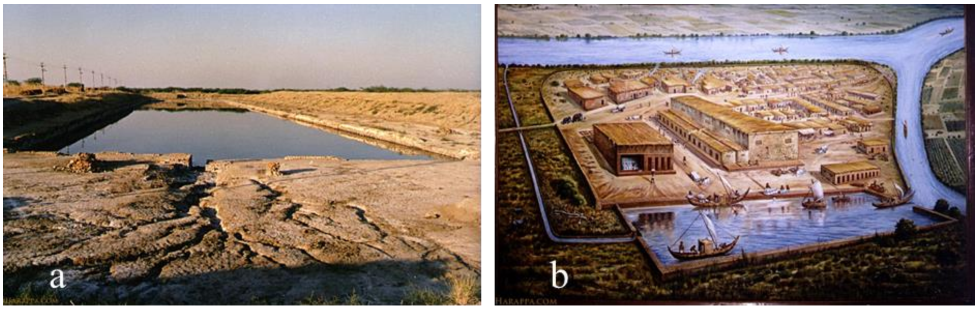

Figure 4: Dockyard (a) and ancient Indus port (b) of Lothal [Source: https://www.harappa.com].